High level of ^{3}He polarization of 81% Maintained in an on-beam ^{3}He spin filter using SEOP

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Abstract

Maintaining high levels of ^{3}He polarization over long periods of time is important to many areas of fundamental and particle beam physics. Long measurement times are often required in such experiments and the data quality is a function of the ^{3}He polarization. This is the case for neutron scattering where the ^{3}He can be used to analyze the spin of a scattered neutron beam and relatively small fluxes of polarized neutrons leads to experiment times longer than several days. Consequently the Jülich Centre for Neutron Science (JCNS) is developing spin-exchange optical pumping (SEOP) systems capable of polarizing the ^{3}He gas in place on a typical neutron instrument. Using a polarizer device we constructed a high level of ^{3}He polarization of 81 % ±2 %was maintained with good time stability. Such levels of polarization maintained over time will be able to reduce the measurement times for such experiments and eliminate time dependent data corrections.

Keywords: polarized 3He, neutron spin filter, spin-exchange optical pumping

1. Introduction

Polarized ^{3}He has been shown to be advantageous when used as an analyzer for polarized neutron scattering, an area of physics research that is growing quickly given its relevance to studies of magnetism and also soft matter. These sorts of experiments are normally conducted in large scale facilities for neutron scattering research where even at the highest flux neutron sources these experiments can require many days of data collection because the measurements are commonly counting statistics limited. Factors such as small sample size and low solid angle coverage of the scattered neutron beam can lead to long experiments. Additional losses in neutron flux caused by the addition of neutron polarizers and analyzers, and also because one now must normally measure four spin states, 2×2, for the two states of incoming neutron spin, and the two states of scattered neutron spin, for each measurement further lengthens required measurement times.

Much work has been done to optimize the use of polarized ^{3}He for use as neutron spin filters (NSF). Routinely experiments using ^{3}He NSF are conducted at many neutron sources worldwide. These experiments include polarized neutron diffraction, polarized neutron reflectometry, polarized small angle neutron scattering and fundamental particle physics [1, 2, 3, 4, 5]. Further, many neutron sources worldwide have programs developing the methods and acquiring the technology for ^{3}He NSF locally for use at their facilities. At the JCNS we have chosen to work on in-situ polarization of the ^{3}He gas using the spin exchange optical pumping method (SEOP) [6]. ^{3}He polarizations of up to 80% in ^{3}He NSF cells have been verified with neutron measurements [2, 4, 7]. In these experiments the ^{3}He was polarized off-line, and thus undergoes T_1 nuclear magnetic decay of the ^{3}He polarization which typically has a time constant of 100-300 hours. Here we present a measurement of 80% ^{3}He polarization but maintained in steady state for 24 hours on a neutron instrument by in-situ optical pumping.

2. In-situ SEOP polarizer

A typical in-situ SEOP polarizer must contain several typical elements. First a magnetic environment with a uniformity on the order of 10^{-4} cm^{-1} in $\Delta B/B$ is required to maintain long ^{3}He T_1 lifetimes. Second, a circularly polarized high power laser source and collimation optics are required for the optical pumping of the dense alkali-metal vapor in the cell. Next a heating source/oven is needed to obtain the necessary alkali-metal number densities which requires temperatures ranging from 170 $°C$ to 250 $°C$. And optionally a transverse RF field for performing adiabatic fast passage spin reversal of the ^{3}He can be installed so that the system can be used also be used as a neutron flipper. Several such SEOP based polarizer have been constructed for NSF [1, 8, 9, 10]A block diagram of our device is shown in Figure 1. Additionally, diagnostics such as a free induction decay system to monitor ^{3}He polarization independent of neutrons and pump light absorption can be installed to aid in system monitoring and optimization. The total length of this device is about 1 meter including an enclosure for laser radiation protection. This device is in many ways similar to the one presented in [11, 12].

Saturation polarization in a SEOP cell is determined from the balance of the alkali-metal ^{3}He spin exchange rate and the total ^{3}He relaxation rate for a certain set of conditions where the spin-exchange rate to the ^{3}He is a function of the number

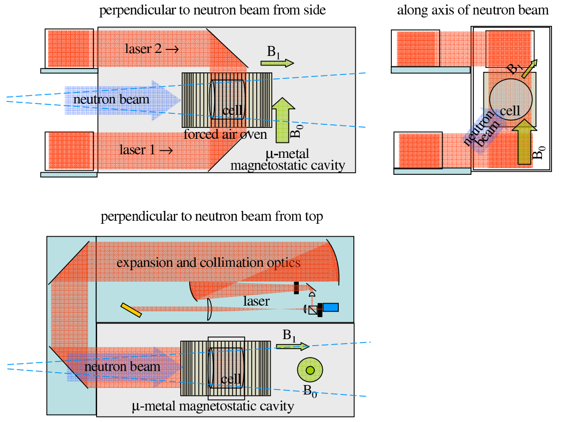

Figure 1: Diagram of the in-situ SEOP polarizer showing the configuration of the magnetic cavity, lasers and optics, RF coil for adiabatic fast passage, oven and cell.

density of the alkali-metal vapor. Typically the maximum polarization in SEOP cells is limited by a ^{3}He relaxation term, called the X-factor, that scales also with alkali-metal number density [13]. While the origins of this relaxation are still not understood, they seem to be a fixed property of a given cell. Typical cells used for NSF have an X-factor of 0.2 to 0.3 times the spin-exchange rate. This leads to maximum ^{3}He polarization in NSF of 70% to 80% when one includes the other sources of ^{3}He relaxation such as relaxation from collisions with the cell walls and dipole-dipole self-relaxation. These latter two effects are added together and cited as the measured room temperature lifetime, or T_1, for the cell. The cell we used, named J1 here and in prior publications, was chosen for this test because it has a low X-factor value and a long T_1 of 660 hours. This cell was produced in the Forschungszentrum-Jülich GmbH glass workshop and prepared and filled with rubidium and ^{3}He in a collaboration with ISIS. It has been characterized in previous neutron tests, where it was polarized off-line, and showed a high level of ^{3}He polarization [7], but was never polarized in-situ. Consequently those measurements involved extrapolation of the ^{3}He polarization to the maximum equilibrium value.

In addition narrow band optical pumping sources, with spectral linewidth comparable to the pressure broadened absorption linewidth of the Rb vapor in the SEOP cell, are necessary to obtain the highest levels of alkali-metal polarization [14]. Narrow band optical pumping sources must therefore be used to obtain maximum ^{3}He polarization because it is also proportional to the average alkali-metal polarization in equilibrium. Consequently the lasers that we choose to use are frequency narrowed using an external cavity [15] which can meet the requirements for polarizing Rb vapor to near unity. The laser must then be expanded to the cover the full dimensions of the cell and collimated to provide the most optimal performance [16].

3. Measurement

The device was installed on the TREFF magnetic reflectometer [17]. It was placed directly after the neutron sample position and electromagnet such that the cell was approximately 90 cm from the sample position. The magnet was run at a nominal 0.01 T field during this test. A single neutron counter was placed behind the system and used to monitor the neutron transmission of the unpolarized incident beam through the ^{3}He cell as a function of time.

The relative neutron transmission, *i.e.* the ratio of transmission, T, of an unpolarized neutron beam through a polarized ^{3}He cell to the transmission through the unpolarized cell, T_0, is

$$\frac{T}{T_0} = \cosh([\mathrm{He}] l \sigma P_{\mathrm{He}} \lambda). \qquad (1)$$

Here [He] is the ^{3}He number density, σ the spin dependent ^{3}He neutron absorption cross section, λ the neutron wavelength, l the cell length, and P_{He} the ^{3}He polarization. Thus by knowing the ^{3}He number density-length-cross section product, and the neutron wavelength, unpolarized neutron transmission is a strait forward method to obtain absolute ^{3}He polarization. The neutron wavelength of TREFF has been previously calibrated and is 4.7 Å± 0.1 Å.

The ^{3}He number density-length-cross section product of a ^{3}He cell can be determined from the unpolarized neutron transmission of an unpolarized ^{3}He cell as a function of neutron wavelength. The unpolarized neutron transmission of an unpolarized ^{3}He cell, T_0 is

$$T_0(\lambda) = T_{\mathrm{E}} e^{[\mathrm{He}] l \sigma \lambda}. \qquad (2)$$

Thus by measuring the transmission as a function of neutron wavelength one obtains a two parameter fit where the empty cell transmission is T_{E} and the value of the exponential is the number density-length-cross section product. In this way the ^{3}He number density-length-cross section product of the J1 cell was measured with a small angle neutron scattering spectrometer KWS1 [18] which has been installed at the FRM II reactor in Garching. KWS1 uses a 10% $\Delta\lambda/\lambda$ neutron velocity selector to change the neutron wavelength. From this measurement the number density length product of the J1 cell was found to be 5.18 bar·cm ± 0.08 bar·cm where the pressure in bar is referenced to 25 °C to convert to a number density.

After optimization of the optical pumping parameters of our system, during which time the cell had already achieved over 74% P_{He}, it was allowed to run continuously for two days without any additional adjustments. During this time the neutron transmission was monitored with the neutron detector. Figure 2 shows the measured relative neutron transmission which has been normalized to the unpolarized cell transmission versus time. The unpolarized ^{3}He cell transmission was obtained directly at the end of the measurement by depolarizing the cell with an intense RF field at the ^{3}He Larmour frequency. Polarization destruction was verified by a nuclear magnetic resonance free induction decay system installed to monitor the relative ^{3}He polarization independent of the neutron data.

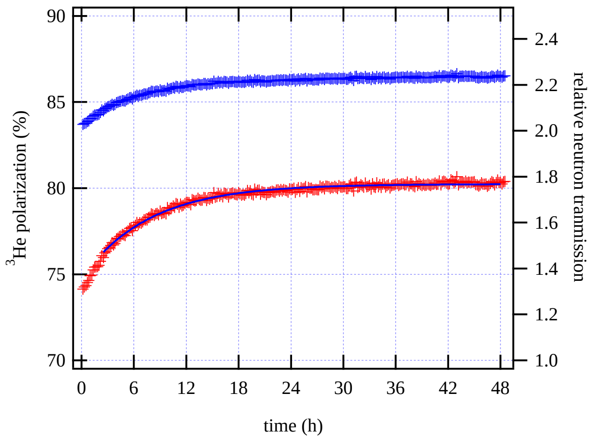

Figure 2: The ^{3}He polarization versus time for the J1 cell, red (left axis) and the neutron transmission relative the unpolarized cell transmission, blue (right axis). A fit to the data gives a spin-exchange time constant for the build up of ^{3}He polarization of 7 hours.

From this data one can see the final transmission of the polarized cell was a factor of 2.23 times the unpolarized transmission corresponding to an equilibrium ^{3}He polarization of 81% ± 2 %. The polarizer was highly stable for the period of the 48 hour measurement. A fit to the data gives a 7 hour spin-exchange time constant which is a typical value for the SEOP method and the absolute polarization was over 80% for the last 24 hours of the measurement.

The in-situ ^{3}He relaxation time of the J1 cell for this experiment was measured before the final polarization measurement by turning off the lasers and the cell heating while monitoring neutron transmission. This data was again normalized to the unpolarized neutron transmission, and the fit gave T_1=351 hours ± 4 hours. The reduction of the cell T_1 from 660 hours to 351 hours is caused by the field homogeneity in our μ-metal cavity being lower when installed on TREFF than what one obtains in laboratory conditions. This adds some additional ^{3}He relaxation du to the field gradients. However, despite this reduction in T_1, it was sufficiently long compared to the spin-exchange rate not to affect the maximum achievable polarization within the accuracy of our measurement.

4. Conclusion

In conclusion, we have measured and maintained a new high-level of ^{3}He polarization for a continuously polarized NSF on a neutron instrument. Being able to maintain this level of polarization will serve to improve the quality of polarized neutron instrumentation using polarized ^{3}He.

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